Relationships between the dimensions of the human aortic and pulmonary valve leaflets: implications on Ross' operation

Abstract The technique of replacing the aortic valve with the patient's pulmonary valve and the implantation of a homograft in the pulmonary position was first introduced by D. Ross in 1967. Despite the many advantages and successes of this procedure, it frequently results in some degree of valve insufficiency. In order to optimize the results of Ross' operation, we carried out a comparative study (n=22) of the relative dimensions of the human aortic and pulmonary valve leaflets using a digitizer. The digitizer supplies the spatial coordinates of a given point (in a pre-chosen reference frame), by the positioning of its sensor on that point. By digitizing relevant points marked on the arterial wall we were able to calculate the distance between the commissures and the perimeter of each leaflet. Analysing the values thus obtained, we found that in 17 of the 22 cases studied (77.3%) there was one orientation (out of the three anatomically possible orientations) of the pulmonary valve, relative to the configuration of the recipient aortic root, that was clearly better than the other two. This study led to the formulation of a "rule" that, in most of the cases studied (86.4%), led to the best fitting orientation of the autograft using the knowledge of the intercommissural distances.

Key words Aortic valve • Pulmonary autograft • Ross operation • Leaflet coaptation •

Introduction

Ross' technique [5, 7] has shown excellent results with the pulmonary autograft adapting efficiently to the higher pressures of the heart's left side [4] and according to Kouchoukos et al. [6], Elkins RC [2, 12], Ross [8–11], Angell et al. [1] and others it is the best aortic valve replacement method. There has been evidence of the valve's growth in children which makes it a highly promising method for the permanent replacement of the aortic valve in children and young adults [3].

From a technical point of view Ross' operation is a difficult procedure often resulting in some degree of valve insufficiency that has been considered acceptable in the past. Recently Angell et al. [1] reported that even a small degree of aortic insufficiency reflects a poor leaflet alignment. As the success of the operation is dependent upon the valve's functioning normally after surgery, it is important that the implantation of the pulmonary autograft in the aortic position leads to a perfect leaflet coaptation. This correct implantation depends on both the surgical technique and the correct choice of orientation of the pulmonary autograft in relation to the anatomic configuration of the recipient aortic root.

We studied the dimensions of the leaflets of the aortic and pulmonary valves to determine if it was possible to establish any correlation between the dimensions of the leaflets of the two valves, and to determine the best orientation of the pulmonary autograft in relation to the recipient aortic root.
Material and methods

The present study was performed in vitro on each pair of aortic and pulmonary valves taken from 22 unfixed human hearts after autopsy. The subjects comprised 12 males and 10 females whose ages varied between 33 and 84 years (mean 62.6 years).

We utilized a Digitizer Pohemus B105A that has a source of low frequency electromagnetic radiation and a sensor capable of measuring, in a given point of space, the value of the electromagnetic field generated by the source. The digitizer then transforms this value in the point's spatial coordinates in a pre-chosen reference frame, with an error of 1/3 mm within a radius of 20 cm from the source. The digitizer was connected to a PC for data acquisition and processing.

Each pair of aortic and pulmonary valves was supported on appropriately sized test tubes with the valves turned inside-out exposing the leaflets. By digitizing points marked (approximately 1 mm apart) on the arterial wall between the commissures and along the leaflets' insertion line on the arterial wall, we were able to compute, for the three leaflets of each valve, the intercommissural distances and the perimeters along the insertion line on the arterial wall. The points marked on each valve were digitized 5 times and the average value was computed. The observation error was taken as the largest of the deviations from the average and compared with the digitizer's error (1/3 mm). The experimental error was taken as the larger of these two errors.

Once the experimental results had been obtained from points marked on the valves, the exactitude of these points was checked by the following experiment. We digitized all the points marked along the line of the leaflet's insertion on the arterial wall and compared the value computed for the leaflet's perimeter with the value computed when every other point was digitized. We found that the perimeter's value, when every other point was digitized, was lower than the value obtained when all the points were digitized and that the differences between those values ranged from 1.5 to 2.9 mm (3–5% of the value obtained when all the points were digitized). The fact that the difference between the perimeters obtained by the two methods previously described is small, indicates that the points are marked close enough to allow a correct estimation of the leaflet's perimeter. Having thus validated the experimental method, we applied it to the 22 pairs of aortic and pulmonary valves.

We performed, for the 22 cases under study, a comparative graphical analysis of the intercommissural distances and of the perimeters between the aortic and pulmonary valves for the three anatomically possible orientations of the pulmonary valve in the aortic position, based on the values obtained for the intercommissural distances and perimeters along the leaflets' insertion line on the arterial wall, respectively. On the x axis we marked the three pulmonary valve leaflets and underneath the three aortic leaflets so as to correspond to one particular possible orientation of the pulmonary valve in the aortic position. On the y axis we marked their respective values in centimeters. We thus obtained two curves, one for the dimensions of the aortic leaflets and the other for the dimensions of the pulmonary leaflets. By performing similar graphical analysis for the other two anatomically possible orientations of the pulmonary valve, we were able to compare the differences between the dimensions of the pulmonary and aortic leaflets for each of the three abovementioned orientations.

The nomenclature used in the present work for the aortic valve's leaflets is: NC for the non-coronary, RC for the right-coronary, and LC for the left-coronary. The nomenclature for the pulmonary valve's leaflets is: FA for the facing-anterior, NF for the non-facing, and FP for the facing-posterior (Fig. 1).

Results

Table 1 shows that some of the valves (mostly the aortic valves) had some sort of lesion which did not interfere with the measurement of the parameters concerning this study. All the valves showed good leaflet coaptation on visual inspection.

Figures 2 and 3 show an example of the graphical analysis for one case. For this particular case the values (and respective experimental error) of the intercommissural distances for the different leaflets are as follows:

<table>
<thead>
<tr>
<th>Predominant lesions</th>
<th>Aortic valve (mm)</th>
<th>Pulmonary valve (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaflet calcifications</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Leaflet thickening</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Leaflet tearing</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>Arterial dilatation</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Slight fusion of the commissures</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>No lesions</td>
<td>5</td>
<td>18</td>
</tr>
</tbody>
</table>

The differences between the dimensions of the two valves' leaflets vary significantly from one orientation to the next. The least squares method applied to those differences provides an objective criteria for determining the best orientation.

For the case under consideration the two kinds of analysis (graphical and the least squares method) indicate that of these three possibilities, orientation A is clearly the best, implying a positioning of the pulmonary autograft in the aortic position such that the following correspondences would apply:
Table 2 Dimensions of the aortic and pulmonary valves’ leaflets. Values given as average plus or minus standard deviation (NC non-coronary, RC right-coronary, LC left-coronary, FA facing-anterior, NF non-facing, FP facing-posterior)

<table>
<thead>
<tr>
<th></th>
<th>Inter-commissural distances (cm)</th>
<th>Perimeters (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aortic valve</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC</td>
<td>2.64±0.42</td>
<td>5.04±0.60</td>
</tr>
<tr>
<td>RC</td>
<td>2.93±0.45</td>
<td>5.24±0.57</td>
</tr>
<tr>
<td>LC</td>
<td>2.61±0.30</td>
<td>5.05±0.53</td>
</tr>
<tr>
<td><strong>Pulmonary valve</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA</td>
<td>2.84±0.49</td>
<td>4.95±0.41</td>
</tr>
<tr>
<td>NF</td>
<td>2.74±0.46</td>
<td>5.10±0.50</td>
</tr>
<tr>
<td>FP</td>
<td>2.75±0.37</td>
<td>5.15±0.43</td>
</tr>
</tbody>
</table>

It is usually accepted that the three leaflets of the pulmonary valve are identical in size. However, our results show that the three leaflets of each valve have different intercommissural distances and different perimeters. Furthermore, they show a large variability among the cases studied as can be seen in Table 2. It can therefore be stated that the aortic and pulmonary valves have differently sized leaflets which has strong implications for the correct choice of the orientation of the pulmonary valve in relation to the configuration of the recipient aortic root. In several cases, it is difficult to decide which of two leaflets is the largest (or the smallest) because the differences between them fall within the experimental error. In the case of the intercommissural distance, this indetermination occurs at the level of the smallest leaflets in four cases, and at the level of the largest ones in 14 cases in either one or both valves. There are two cases exhibiting both types of indetermination. In the case of the perimeters, there are two cases of indetermination at the level of the smallest leaflets, six cases at the level of the largest ones and 12 cases with both types of indetermination.

We found that, in 17 out of the 22 (77.3%) cases, there is one particular orientation of the pulmonary autograft that is clearly better than the other two. In the remaining cases the orientation was either not significantly better than the other possibilities, or there were two very similar orientations. Further, we found that in eight cases (34.6%) the best orientation was the one for which the following correspondences between the pulmonary and aortic leaflets applied:

\[ \text{FA} \leftrightarrow \text{RC} \]
\[ \text{NF} \leftrightarrow \text{LC} \]
\[ \text{FP} \leftrightarrow \text{NC} \]

in nine cases (40.9%) the best orientation was:

\[ \text{FA} \leftrightarrow \text{NC} \]
\[ \text{NF} \leftrightarrow \text{RC} \]
\[ \text{FP} \leftrightarrow \text{LC} \]

and in three cases (13.6%) the best orientation was:

\[ \text{FA} \leftrightarrow \text{LC} \]
\[ \text{NF} \leftrightarrow \text{NC} \]
\[ \text{FP} \leftrightarrow \text{RC} \]

None of the above possibilities is dominant, meaning that out of the three possible orientations there is not a privileged one to be chosen for all cases.

However, when we compared the results of the two types of analysis previously described with the values of the intercommissural distances, we were able to formulate a “rule” which led to the best fitting orientation for the autograft from the knowledge of the intercommissural distances. We found that:

1. In 14 of the cases studied (63.3%) the orientation is determined by pairing together the leaflets of both valves with the smallest distance between commissures.
2. In three cases (13.6%) it is not possible to tell which leaflet has the smallest intercommissural distance, and in these cases the correct orientation is determined by pairing the leaflets with the largest intercommissural distances.
3. In two cases (9.1%) there was an ambiguity as to which was the leaflet of one valve with the smallest intercommissural distance, and which was the leaflet of the
other valve with the largest intercommisural distance, so that pairing off the smallest leaflets led us to one orientation and pairing off the largest ones led us to another orientation. However, the graphical analysis of the distances between the commissures and the perimeter and the analysis of the least square values had led us to precisely the same orientations.

4. In 19 out of the 22 cases studied (86.4%) the results from the graphical analysis and least squares method conformed to the above "rule".

Discussion

Ross' operation is the most physiologic procedure of aortic valve replacement. Ross described it as an autograft implant in sub-coronary position. It is the only surgical technique that has had proven excellent results up to 25 years after surgery. Still, quite a few patients have autograft insufficiency after surgery. To overcome this problem many authors have chosen to perform the Ross operation as a miniroot or whole root technique. Only with time will it be known if such approaches will be better than the sub-coronary replacement. We still continue routinely to perform the Ross operation as a sub-coronary implantation and aim at reducing its degree of residual autograft insufficiency.

We have tried to improve the understanding of the mechanisms of the aortic and pulmonary valve leaflets by looking at their morphology. The aortic valve is a three-dimensional structure, and its opening and closing mechanisms are dependent on the movements of the sino-tubular crest and of the base of the so-called aortic annulus. The ideal position for the autograft will be the one where less distortion is induced after implantation. In our study we described, like many authors previously, that most times there are significant differences in cuspidal size. Therefore, it is likely that matching the sizes of the cusps of the pulmonary valve in the aortic root will cause the least distortion and insufficiency both earlier and later after surgery.

Having measured the aortic and pulmonary valves' intercommisural distances and perimeters along the leaflets insertion line on the arterial wall we established, for the 22 cases studied, that both valve leaflets have different sizes. This statement is supported by the fact that the experimental error associated with our measurements of the intercommisural distances varies between 0.06 cm and 0.17 cm (which represent approximately 1.9% and 5.4% of those values), whereas the standard deviation to the mean (Table 2) varies between 0.30 cm and 0.49 cm (which represents 11.5% and 17.2% of the average value of the intercommisural distances). We obtained slightly larger differences between the experimental error and the standard deviation for the perimeters. These facts have strong implications for the correct choice of the orientation of the pulmonary autograft in relation to the recipient aortic root.

Our study shows that in most of our 22 cases it was possible to determine the best fitting position by pairing the smallest cusps of the aortic and pulmonary valves. In the event of its being difficult to determine the smallest cusps, then the largest ones should be paired. Performing these measurements in surgery is possible by introducing a valve sizer into the root of the aortic and pulmonary valves, and marking the relative position of the commissures on it.

We hope to improve our results of aortic replacement with autografts and homografts through the application of these concepts.

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The experimental errors associated to the perimeters have values of similar magnitude.